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Potential renewable energy resources of the Lerma Valley, Salta, Argentina for its strategic territorial planning

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A B S T R A C T

Renewable energy sources are considered as strategic opportunities to improve the population's quality of life, to promote the development of more efficient and equitable economic systems, and to favor environmental sustainability in the territorial planning of Lerma Valley (Salta, Argentina). The mapping in raster format (each pixel having a reference value) of the potential renewable energy sources (solar, wind, biomass, hydraulic, mixed) is essential to define ideal locations for different types of renewable applications, and to plan suitable strategies for its implementation. It is necessary considering environmental diversity and site conditions (topographic, natural resource, infrastructure and service availability, social and economical) of the intervention area.

Different methodologies are used for mapping of potential energy resources. Solar radiation is spatialized through the application of statistical regressions between altitude, latitude, precise incident solar radiation records, and radiation data estimated with the Geosol V.2.0.™ software. The Argentina Map program is used for the wind potential resource modeling. It requires as inputs: a Digital Elevation Model, a land use and cover map (to determine roughness), and measured and/or estimated wind speed and frequency data. The hydroelectric potential for microturbine applications is calculated from the topographic drop and the annual mean flow in cumulative models, through the application of the Idrisi Kilimanjaro™'s runoff tool; while the power densities are compared at the watershed. Biomass potential (at this exploratory stage), is interpreted from the available biomass type (land use and cover map), its energy application availability, and some quantitative indicators associated with the biomass types identified as priority.

In conclusion, the renewable energy potential in Lerma Valley is very high and diverse, and its close connection with social–environmental conditions is basic for the creation of energy resource-related territorial plans.

Contents

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1. Introduction

1.1. Strategic planning and Territorial Ordination as work framework

The assessment of different renewable energy (RE) types (solar, wind, hydraulic and biomass) as productive-environmental alternatives for the Territorial Ordination (TO) of the area, is considered in the framework of an investigation project and the "Territorial Ordination of Lerma Valley" postgraduate scholarship [1,2]. Non-conventional energy evaluation is considered in this context as a strategy for regional development and improvement in the quality of life and the environment.

TO is considered the spatial projection of a social and economic development strategy. As explained by Gómez Orea [3], this entails a type of planning that includes economic and physical aspects through an interdisciplinary and transdisciplinary approach.

In the territorial diagnostic assessment of Lerma Valley – approached by means of field trips, interviews and participatory multidisciplinary and multi-sectorial workshops – non-conventional energy sources are revealed as potential opportunities for the region. In the strengths, weaknesses, opportunities, threats (SWOT) analysis [2,4] renewable energy sources appear specifically associated with weaknesses such as: inadequate residential/agricultural/livestock waste management, unplanned urban growth, production system inefficiency, and unmet basic needs of the isolated population in mountainous areas; threats related to environmental degradation and potential energy crisis; high-agro-ecological potential and growing environmental awareness strengths; productive development and regional planning opportunities.

The main idea of the project is to analyze the RE implementation possibilities in a territorial model that is environmentally and economically sustainable. Therefore, renewable energy sources appear as strategic options to: revitalize "forgotten" areas (remote mountain zones); improve the quality of life (access to services); cover the growing energy demand of productive and social systems; prevent, minimize and/or mitigate environmental impact generated by production activities; create various economic undertakings; boost sustainable exploitation of the natural resources; respond in the event of a collapse of the traditional energy production systems associated to natural and/or anthropogenic risks.

In relation with the various renewable energy options, the transformation of biomass energy from residential and production waste is identified as priority in the participatory assessment for the valley area. For the mountain area, various solar and hydraulic microturbine applications are more highly valued as direct answers to the improvement of the access to services and productive system efficiency, and as indirect answers to contribute to the withholding of the rural population, preventing the current strong "mountain emptying" tendency.

As detected in the participative territorial diagnostic assessment, the approach to renewable energy from a multidisciplinary perspective integrated into the environment is key to the zoning and territorial planning processes. However, the incorporation of particular renewable energy sources in this decision making process requires in-detail analysis of the zone's energy potential to determine the technology selection, development and adaptation, and assure the efficient performance of the renewable applications intuitively proposed by the different social groups. The renewable energy potential map development appears as a concrete tool to answer this query.

The addition of RE to the energy planning processes has been dealt with in prior work, with some tools similar to the one supporting the conceptual framework of this research, such as SWOT [5] and multi-criterion analysis [6,7].

1.2. Energy potential mapping and geographic information systems (GIS)

Geographic information systems (GIS) constitute the work platform for the renewable energy potential mapping since they allow to: integrate the available information into a single organized and interactive system, generate new information through the development of spatial instrument patterns, and efficiently visualize and promote the generated information.

The energy potential mapping is conditioned by

- Vast diversity of environmental units and topographic variability in the work area.
- Lack of basic information about the environmental variables of interest to the definition of the energy potential such as continuous climate records distributed in the whole area, river flow records, precision topographic base maps, biomass volumes, etc.
- Impossibility of assessing field variables due to accessibility limitations, cost, space and time representativity (i.e., specific and/or short series records are not significant).

In this situation, the development of space–time, mathematical, statistical and computing models constitutes an efficient alternative for overcoming zoning difficulties and meeting the need of base information for the energy potential definition. Digital models present the advantage of the possibility of representing the

assessed variable [2] in raster format (the whole geographic space segmented in discrete units—cells). The diversity of the considered variables requires the development of specific spatial models of diverse complexity and detail, according to the assessed renewable energy potential type (solar, wind, hydraulic, biomass).

No references were found for the study area as spatial mapping precedents of this type of variable. Within the country there is some work on a universal scale or developed for other zones, among which stand out: general heliophany charts and satellite climate data records for Argentina [8,9], wind maps for Argentina [10], climatology of the NW of Argentina [11], and forested biomass estimations for Argentina [12]. The work of Ramachandra and Shruthi [13] for Bangalore, India, in the field of renewable energy potential mapping is outstanding. As more integral international experience, it presents a conceptual similarity with this investigation in that the posing and analysis of the renewable potential energy resource used GIS tools even if the territorial characteristics and the concrete instruments used for mapping are different. The need for estimation of the spatially available energy resources to develop better energy management and planning strategies, ensuring resource sustainability, is posed in this research. The work of Sahir and Qureshi [14] also stands out with a more integral vision, although oriented more to the economical and social aspect. In their work, solar, wind, biomass and hydroelectric microcentral renewable resource potential is analyzed but in connection with its practical limitations.

1.3. Work area: Lerma Valley, Salta, Argentina

As defined in the general project [1], the work area includes the province of Salta, known as Lerma Valley, as a geomorphologic unit. It includes urban, production and natural areas and extends over an area of about 5700 km^2. It is located between the following geographic coordinates: latitudes 24°22.0′S and 25°43.0′S and longitudes 65°15′W and 65°48′W. The watershed is considered as the limit of the work area, proposing an integrated analysis at a hydrographic basin level.

The Lerma Valley environmental system basically includes two large and distinct landscape units:

- *Valley between the mountains*. It is specifically restricted to the lower valley area. Most urban and population centers, agricultural and livestock intensive activities and the main means of communication are concentrated here.
- *Mountain*. It includes the sides of the mountain range surrounding the valley up to the watershed. The slopes which outline the west valley area are over 5000 m above sea level, while the mountain range to the east is up to 2000 m above sea level. Its disperse population, extensive production activities and diverse natural environmental units are characteristic.

2. Renewable energy potential evaluation

The following environmental variables for renewable potential mapping were defined: solar radiation (solar power), wind speed and eolian potential (wind power), topographic potential difference and water availability (hydraulic power), available biomass types (biomass power). Different methodologies and processes were selected and rehearsed for each of these variables in order to create the digital cartographic models, as described in the following sections.

Several influential factors relate to the variables being studied or result in transitional steps for its definition; they were spatialized as theme layers through the application of various modulus and digital processing techniques: surface analysis (interpolation, topography, feature extraction), reclassifications, consulting operations (statistics, measurements, comparisons) and logical-mathematical operations (with scalars and between images). In some cases, methodologies were adapted and new functions were developed for the application of the instrumental models in the GIS context.

The software packages used for the development of GIS and digital modeling were: (1) Idrisi Kilimanjaro™, ArcGIS 9.0™, Carta Link 1.2™, CAD™; (2) for statistical analysis and information presentation: Info Stad™, spreadsheets, text processors; (3) for the determination of the energy potential of different resources, specific programs: Geosol V.2.0.™-solar; Argentina Map™ and Wind Rose™—wind. All of the digital cartography was projected to the Gauss Krüger plane coordinate system, strip 3. WGS 84 was the datum used (most common in Argentina). The cartography had to be adjusted to the geodesic system (geographic coordinates—latitude–longitude) and/or to the Universal Transversor Mercator (UTM) for the development of models in order to cover the specific requirements of the supplementary models used. The recognition work scale (1:100,000) was used for the theme maps and digital models creation, which is convenient for a regional approach.

The renewable energy resource assessment is considered in this work with a macro-territorial perspective, which implies the identification of sectors with different degrees of exploitation potential in an initial approximation at recognition level. More detailed studies should be presented for site-specific location, applicable technology types, concrete energy performance, etc.

2.1. Solar energy

2.1.1. Mapping methodology

Solar radiation constitutes the main variable for energy potential analysis for solar applications. Radiation map development for Lerma Valley was based on the combination of various methods: calculated radiation, statistical and GIS processing [15].

The input variables required by each method were confronted with the available data for the study area for the *selection of the solar radiation estimation method*. Precision levels of the obtained estimations were also analyzed for the case of the locality of Salta, which has actual precise solar radiation measurements.

Page's clear-sky method, Hottel's clear-sky method and Liu and Jordan's monthly average day method [16], all with available application in Geosol V.2.0.™ software, were compared. We selected for mapping Hottel's clear-day method for altitudes lower than 2500 m above sea level, and Page's clear-day method for higher altitudes.

Using Idrisi Kilimanjaro™ software's statistic tools we made random, systematic and stratified samplings of 150 and 200 points over a Digital Elevation Model (DEM) of Lerma Valley's terrain. The DEM was generated from NASA's data, with a resolution of 90 m [17]. As the radiation value depends directly upon altitude, the *random stratified sampling* with 200 points was confirmed as most representative of the study area for solar radiation estimation by means of a frequency histogram.

The *Hottel method* H.C. [16] includes in its formulation three coefficients that depend on altitude and geographic location (values available in the area's digital cartography). The altitude and geographic position values (latitude and longitude) for the 200 sampling points were extracted and exported from Idrisi Kilimanjaro for their management in databases and spreadsheets.

The radiation value was calculated at each point for month's Julian day with the Geosol V.2.0.™ software. The radiation on horizontal surface (inclination of 0°) calculation, GTM time zone −3 h and albedo 0.3 were used in all cases. The option "mid-latitude summer" was used for the months of October through

March and "mid-winter latitude" for April through September. Geosol V.2.0.™ software allows parameter calculation and graphic expression: (1) the time of sunrise and sunset, (2) duration of the day declination of the sun, (3) direct, diffuse and total solar irradiation in MJ/m^2 – this variable being of greatest interest for this study – and others [15].

Due to the limitations of the Hottel method for the radiation estimation in places located above 2500 m above sea level, *Page's method* was alternatively used for the radiation calculation of these points. Page's method requires temperature and relative air humidity values as input data, with which the Geosol V.2.0.™ program estimates the partial pressure of steam. Atmospheric turbidity, a parameter also considered by this method, is calculated by Geosol V.2.0.™ by means of a correlation which only depends on the altitude of the place [16].

The mean temperature values were extracted from monthly mean temperature models developed for Lerma Valley in the same Territorial Ordering Project [18].

Due to the lack of exact relative air humidity data (RH) for the zone, with only four historical record stations in the study area: Salta, Las Costas, El Carril and Coronel Moldes [19]; we resorted to using the climate atlas developed by Laboratorio Climatológico Sudamericano for the NW of Argentina [11]. Mean relative humidity maps are available for the months of January, April, July and October. Isolines were digitalized in a CAD™ program in order to generate the raster model by interpolation in the Idrisi program. Finally, the RH values were extracted for the 50 stratified sampling points located 2500 m above sea level [15].

The temperature and RH data extracted from digital models were used in Geosol V.2.0.™ software for the clear-day radiation calculation with Page's method, to adjust the estimation in high zones.

Finally, different mapping methods were tried for the *monthly radiation models*, which can be basically placed into two groups:

- Direct interpolations with GIS tools from the radiation data estimated for each month.
- Analysis of correlations and simple/multiple regressions between estimated radiation and climate/topographic variables (altitude, latitude, longitude) for each month and comparisons between months.

For the interpolation case, two methods were analyzed with the Idrisi Kilimanjaro™ software: nearest neighbor linear interpolation using 6-point search radius ("Interpol" module) and interpolation with TIN module, based on the generation of an irregular triangle network.

2.1.2. Results

The statistic correlation and regression method with altitude (Fig. 1) turned out to be more precise than interpolation [15] for mapping, which is why this method was chosen for the generation of the final solar radiation estimation maps.

The correlation analysis performed between the radiation estimations for the sampling points, showed a very high-radiation correlation with altitude ($R > 0.9$). The altitude correlations were not significant, which is explained by this parameter's scarce variation in the study area extension (about 1°). With respect to the variable longitude, it cannot be considered independent from altitude in the Lerma Valley case, where altitude variations are strongly related to the E–W distribution (narrow valley); the correlation coefficients resulting equally low. The better adjustment for regression by the altitude correspond to second-order polynomial equations with $R^2 > 0.92$. Logarithmic and potential

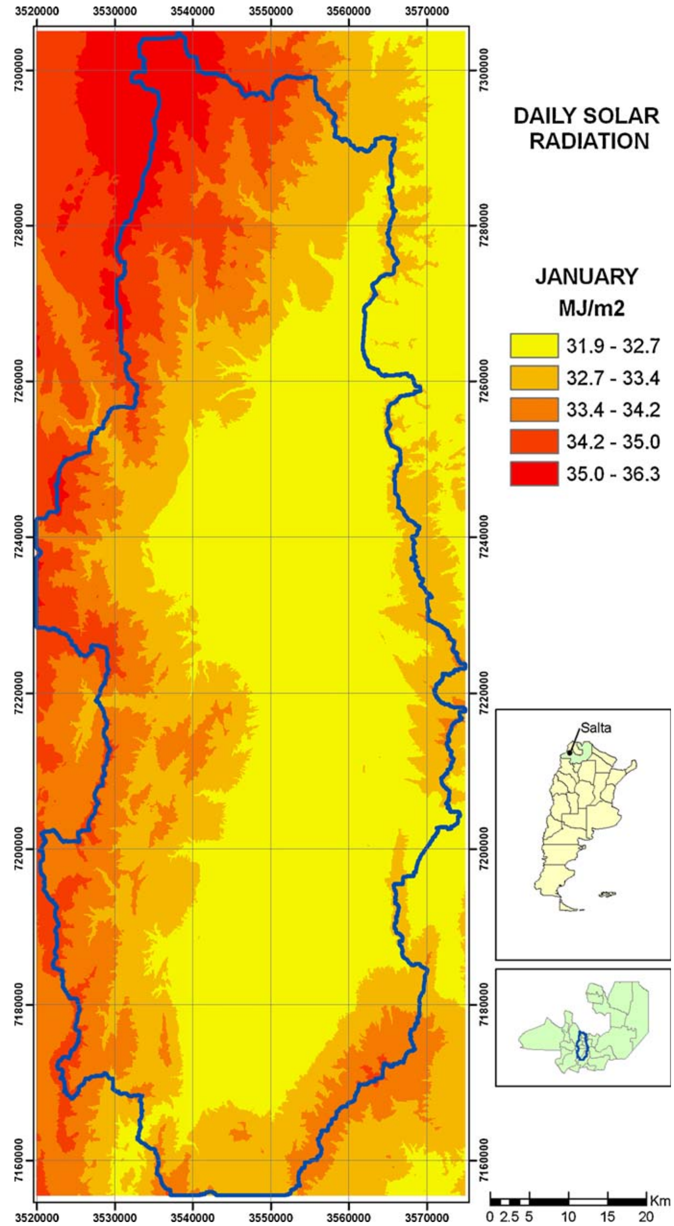

Fig. 1. Map of daily clear-day total radiation for January.

models also presented high R^2, although with underestimations of solar radiation in high zones [15].

In the study of correlations between the radiation values obtained for the various months, a strong linear relation between them was observed ($R^2 > 0.9$), due to which solar radiation estimation was considered for the months for which no complete series (corrected above 2500 m) is available from linear regressions with complete monthly series.

The radiation values obtained for the summer months vary between 29 and 35 MJ/m^2, while those for winter months range between 14 and 22 MJ/m^2. The minimum values correspond to the valley's low areas, radiation increasing with height as defined in the regression statistic models.

2.1.3. Interpretation and discussion

Considering the non-existence of solar radiation records for the Lerma Valley area, GIS computer tools associated with specific

solar radiation estimation programs (Geosol V.2.0.^{TM}) constitute a valid alternative for the mapping of this variable.

Solar radiation presents a decisive relationship with altitude in the work area. This is why maps generated by regressions with this parameter are more adequate than those classically generated by interpolation (with better applications in level field).

The total average day radiation variations present a linear correlation between months, which allows monthly radiation estimations from other month's calculated or measured data. Besides the mapping applications, this monthly interrelation could be interesting for series extensions or extrapolations in which field measurements of only a few months are available.

The total clear-day radiation maps obtained in this work should be adjusted with variables such as orientation, cloudiness and/or heliophany for the generation of radiation spatial models that consider interferences in incident radiation.

The radiation values estimated in the models indicate a high potential in the whole study area for the development of various solar energy applications (thermal, chemical and electrical). This solar energy potential increases in direct proportion to height. Although during the summer solar radiation values get up to between 64 and 100% higher than in winter, the effects of cloudiness not considered in this analysis have a marked effect during the summer, which reduces the solar energy potential during this period.

2.2. Wind energy

2.2.1. Mapping methodology

Wind mapping was produced with the Argentina Map^{TM} program, a version adapted for Argentina of NOAL software, developed in the 1970s for the U.S. Department of Energy. It is based on a mass conservation model that intends to find divergence-free wind speed fields based on observed initial winds [20]. The necessary inputs for the development of the wind models in this program are: DEM, roughness map, wind records from weather stations and wind estimations from the Wind Rose^{TM} program for areas with no local measurements [21].

The *DEM* used for the Lerma Valley was generated from NASA's data with 90 m resolution [17]: 61% of the area is included in an altitude range of 1000–2000 m above sea level, 25% is between 2000 and 3000 m above sea level, and the remaining 14% is over 3000 m above sea level.

A cover map of Lerma Valley was used as an input for the roughness layer, resulting from a non-supervised classification of Landsat 5 image (30 m resolution) [22]. The urban area surface was updated by means of visual interpretation of recent satellite images. Ground coverage was reclassified to roughness, adapting the categories quoted by Mattio [20] to local conditions. The roughness index varies from 1 to 0, the highest values corresponding to greater roughness (woods, city) and the lowest to less rough conditions (clear areas such as uncovered ground and bodies of water). Extreme roughness values are strongly represented in Lerma Valley: about 43% corresponds to very low roughness – water course, reservoirs, uncovered ground and cultivated areas – and a similar percentage (41%) to high roughness—environmental units of humid, semi-humid, "chaco serrano" (dry forest) and transition forested mountainsides, and urban areas.

The National Weather Service's *wind stations* with speed and direction records included in the system were: Salta Capital-Airport (only reference station within the work area), Jujuy—Airport, Orán and Tucumán. The prevailing wind direction of the additional stations was adjusted to 60° (prevailing wind direction of the Salta reference station).

Due to the lack of stations with wind records within the study area and its surroundings, it was necessary to include *estimated wind values* based on other sources. In this way new input data was obtained from satellite data and from the Wind Rose^{TM} software to complete wind modeling spatially. Since the topographic factor is the one that particularly defines the work area characteristics (due to the large range in altitude, from 930 to 5300 m above sea level), a 34-point stratified by altitude sampling was performed to generate the additional wind information through the Wind Rose program. The stratified sampling was carried out over the DEM, using Idrisi Kilimanjaro^{TM}'s statistic module "sample" (spatial sampling) [21].

Finally, the topographic roughness and near-surface wind parameters were included in the Argentina Map program, varying the simulation initialization options until the generation of the model with better adjustment for the zone was achieved.

2.2.2. Results

The digital average wind speed models were generated for heights of 50 m (usual height of wind-driven generator installation) (Fig. 2) and of 10 m. This allows us to make comparisons with weather stations' records.

Final wind maps indicate velocity variations between 1.59 and 7.26 m/s at 50 m and between 0.59 and 6.92 m/s at 10 m. It is important to emphasize that the simulations performed with computer programs correspond, in existing cases, with the data registered in the corresponding weather stations.

The generated wind maps indicate moderate velocities for the low-valley zone (average was approximately 2.5 m/s), which increase with height reaching their maximum values in the mountain divining line and gorge (7 m/s). Velocity is higher in the valley than it is in hillside with native forest, which may be attributed to the effects of roughness. On the contrary, in the important water reservoirs (Embalse General Belgrano—Dique Cabra Corral) wind speed is higher than in the rest of the valley due to its lack of roughness.

As regards wind maximum power, the model produces a maximum value of 632.5 W/m^2 in the highest ridge sectors where the wind speeds are higher.

2.2.3. Interpretation and discussion

Wind maps allow defining areas with energy exploitation potentials of the wind resource. In the low-valley area between the mountains, seasonal wind discontinuity (July–August—months with greater frequency and intensity) together with average velocities lower than 5 m/s allow to infer little implementation possibilities for wind farms with wind-driven generators in the area. More complex studies considering the characteristics of the wind resource as well as a comparison with other energy sources and social–economic components should be taken into account to evaluate the implementation of wind mills (for production uses and water pumping) and/or mixed systems (solar–wind, biodiesel–wind, etc.) in these areas [21].

Wind potential, on the other hand, is more promising in high sectors (mountain peaks and divining line), reaching average velocities higher than 7 m/s and maximum power of 632.5 W/m^2. However, in these isolated sectors with strong topographic barriers for access and energy distribution, location and technical–economical–social feasibility studies must be conducted to assess the possible generation of energy from this resource.

Finally, the generation of wind maps for mountainous areas must consider various adjustments: scale (with greater detail due to the topographic irregularities that are lost in large scales), coverage classifications, checkpoints for wind estimation in areas with no records, and prevailing wind data. In this way it is possible

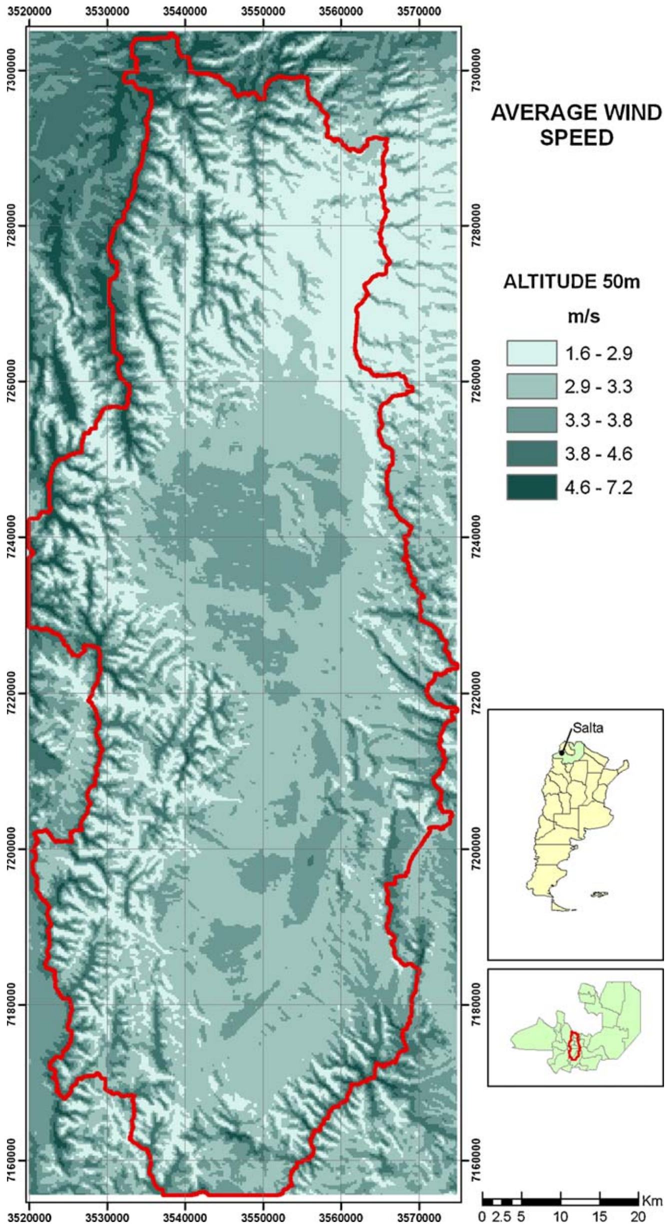

Fig. 2. Map of average wind speed at an altitude of 50 m.

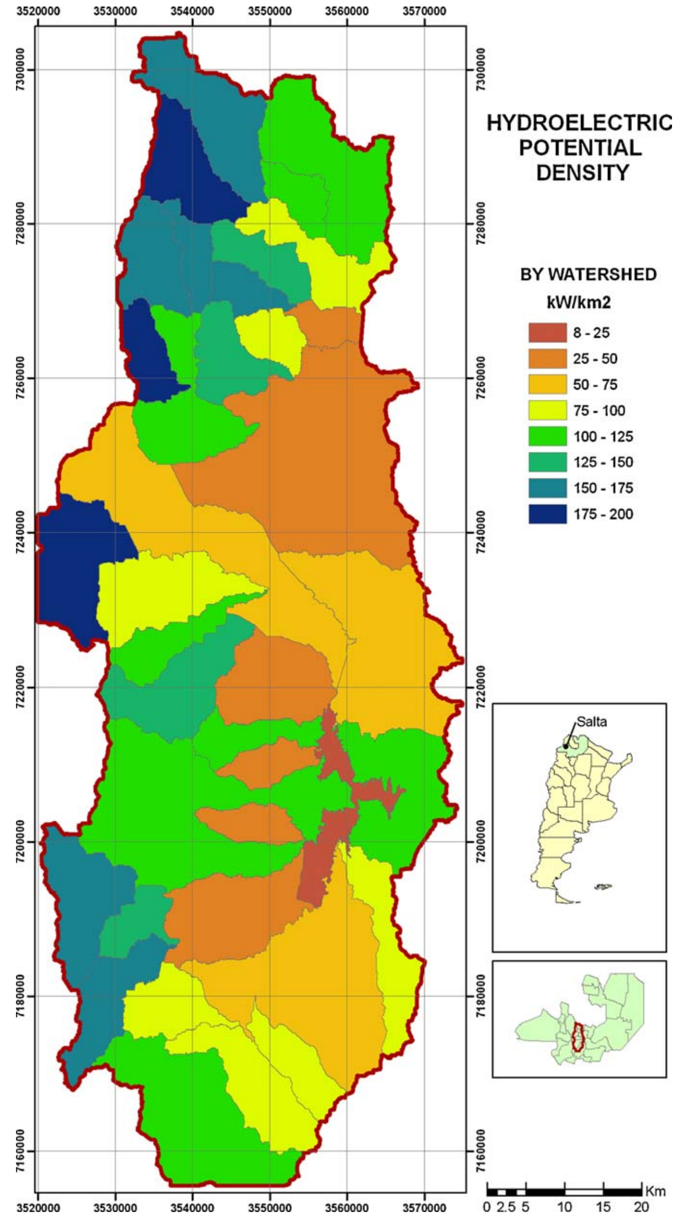

Fig. 3. Map of theoretical brute hydroelectric potential density by watershed.

to optimize the generated models, increasing mapping precision and reliability in complex areas.

2.3. Hydraulic power

2.3.1. Mapping methodology

Just like for the energy potential assessment of the other renewable sources analyzed, the hydraulic resource analysis must recognize two stages: one strictly macroregional to identify the resource's suitability and to select areas of interest for its exploitation for hydroelectric purposes and another strictly local to select and assess the potential of several locations (in this case, hydroelectric microcentrals in the water streams within the selected areas of interest) [23].

The indicators proposed by Muguerza [23] are used for the hydraulic potential assessment of Lerma Valley. The first one of these is the *theoretical brute hydroelectric potential*, which assumes that total power delivered by the water volume runs through a general course from a higher to a lower height and that there are no leaks of any kind. The second one is the *hydroelectric technically exploitable potential*, which assumes real potential with technical exploitation feasibility, implying that all available water volume is to be used for the production of energy.

The following criteria are taken into consideration for its development:

- The water streams are torrential, conditioned by the existence of two distinct hydrologic seasons (dry season May–October, rainy season November–April). This is the reason why the mean annual flow value is proposed as a water availability indicator.
- The development of digital models for spatial mapping of the variables being studied allows making up for the lack of gauging data in the work area. In this sense, methodologies developed for maximum water flow calculation with GIS tools by the same work team [24,25] are applicable and transferable to this

particular case for the estimation of annual outflow, annual mean flow, and topographic drop.
- The use of the Idrisi Kilimanjaro ™ software's "Runoff" module [26] allows flow estimation in spatial accumulation models of water volume per pixel. In this application each pixel is considered conceptually as the minimum basin unit, resulting in the estimated flow values through basins and sub-basins of the accumulated flow, pixel by pixel within them.

For the *theoretical brute hydroelectric potential*, digital models were previously developed for the variables: annual outflow, annual mean flow and topographic drop. The flow and annual outflow values were estimated through the runoff module of the Idrisi Kilimanjaro™ software and adjusted through polynomial correlations ($R^2 = 0.98$) with hydrologic gauge series [27].

The inputs used for modeling were: DEM, income volume of water to the model (mean annual precipitation map [18] multiplied by real pixel area – horizontal projection adjusted by slope), and infiltration factor. Infiltration rate image was calculated from the curve number (CN) conceptual method [28], which considers ground hydrologic groups (texture characteristics) and cover types (hydrologic type and condition) and through a relation with infiltration indexes [29]. Nonexistent depressions in the terrain generated by the interpolation of altitude data were removed by "pit removal" function [26].

Equations developed in the GIS context [24,25] for the calculation of concentration time in maximum water level calculation were applied to induce real topographic drop (height gradient) in the work area.

Continuous power was estimated in raster format through the product of accumulated annual mean flow (mass) per pixel, height gradient and a gravity acceleration factor. The *annual theoretical energy* to continuous power results from referring theoretical brute hydroelectric potential to time units [23].

Drainage areas were defined for the calculation of density. They were generated by applying Idrisi Kilimanjaro™ software's "Watershed" module (which automatically originates them from a DEM), being reclassified, adjusted and nominated according to the zone's cartography [30–32]. *Theoretical brute hydroelectric potential's density* results from the relation between total power and area of watersheds. Although there is no experience in monitoring this type of system in the watershed of the NW of Argentina for the calculation of *hydroelectric technically exploitable potential* indexes, it was determined for guidance purposes by the United Nations Economic Commission for Europe, based on defined minimum and maximum technical potentials in relation with the specific density of brute potential [23].

2.3.2. Results

The continuous power and theoretical annual energy maps showed a considerably greater potential for the development of small-scale hydroelectric applications in the high areas versus the valley area. The theoretical brute hydroelectric potential exceeded the 20 mW in some mountain watershed.

The calculation of the power density allows a better visualization of the basins' quality with the aim of energy exploitation [23]. Regarding this parameter (0) the watersheds with greater theoretical potential density were (Fig. 3): Corralito (192 kW/km^2), Usuri (187 kW/km^2), and Huaico Hondo (181 kW/km^2). The watersheds that stand out with a density greater than 150 kW/km^2 are: Chilo-Ampatapa, Castellanos, Río de las Nieves, La Calderilla, Cuesta Grande and Churqui. The identified watershed with greatest theoretical brute hydroelectric potential density coincides with the area where the only one existing hydropower plant (Corralito) [33]. The microturbines system is based on different tributaries (Puyil and Manzano streams), regulation work (small reservoirs), and channels that deviate water to the central ensuring the water supply during the whole year. It is integrated to the national net with an total potency of 13.2 MW [34].

From the hydroelectric technically exploitable potential analysis it can be induced that 49% of the study area presents an exploitation potential of types 4 and 5, making up 10–45% of the theoretical brute hydroelectric potential (given that the total available flow is destined for energy production). No watershed with a density greater than 200 kW/km^2 was found within the study area. Therefore, hydroelectric technically exploitable potential of types 5, 6 and 7 are not represented. They were defined in the bibliography with an exploitation percentage of up to 60% of their theoretical brute hydroelectric potential [23].

2.3.3. Interpretation and discussion

There is a high-hydraulic potential in the Lerma Valley area for the implementation of energy exploitation of microturbines, particularly in the mountainous areas. Although the mean annual flows are not the maximum in the high areas (generally the flows accumulate towards the low areas), the strong topographical gradient conditions these areas as the most favorable for the implementation of hydroelectric microcentrals.

The mountainous areas in the west of the valley have the highest potential as a result of a combination of optimum conditions (high slopes and greater volumes of water entrance). The south and east areas of the valley do not present such a high-hydraulic potential since in spite of the topographic drops being significant, the area is drier and therefore the water flows are lower.

The obtained results constitute indicative values of the potential of the area which are independent of the technologies to be applied. However, the annual variability conditions of the hydraulic pattern make us think of applications with reservoirs in order to cover communal demands (main alternative for batteries charging) or of integration to the national electrical network. The possibility of installing small microturbines for domestic consumption (of the central type, which take advantage of minimum permanent flows), requires specific location studies which exceed the regional view of this work.

Research of technical, economic, and social viability should be done before defining specific location for the work. Furthermore, due to the torrential conditions of the area, it will be essential to include a detailed analysis about risks, considering contingencies and frequent erosive processes in the area for the design of hydraulic applications.

2.4. Biomass energy

2.4.1. Analysis and mapping methodology

The diversity of biomass energy sources showed in the Lerma Valley and the non-existence of field compiled data associated with available volumes and performance, render difficult its quantitative mapping at this general scale of acknowledgment. Nevertheless, as the aim of the work is to define territorial capability for the implementation of RE in the area at an exploratory level, it is relevant to make a qualitative analysis of the different types of available biomass in order to orientate the evaluation of this energy potential.

The biomass resources may be defined as: potential or existing resources (including all those that can be found in the territorial unit without considering other uses for them), available resources (those potential ones with exploitation viability) and usable resources (those available without economic, technical, social or access barriers) [35].

In this sense, in specific analysis proposals of this potential [35] and mapping antecedents of the biomass resource [12,36–38], there are three levels of approach recognized for its evaluation:

1. Biomass energy potential estimation from present biomass type recognition and interest in its energy exploitation. In current and future scenarios, the diversity of available biomass resources is valued.
2. Selection of the energetically most interesting resources and their quantization as a resource generated by surface unit (i.e., agricultural waste volume by type/hectare) or generation rhythm (i.e., biomass industrial waste volume/day).
3. Estimation of the energy capacity on the basis of its intrinsical, physical, and chemical properties (calorific power, ashes composition, etc.). It is a detailed analysis that requires precise measurement for each type of evaluated biomass.

Coinciding with the general analysis set up for the other renewable energy resources (solar, wind, hydraulic) the evaluation of the biomass potential for Lerma Valley was calculated based on the first approach and a qualitative–quantitative advance over the following points. Currently, a more detailed analysis of the biomass energy potential is being developed for one section of the work area, which is particularly oriented to the quantization of the most representative resources (tobacco and chili pepper cultivation, prevailing types of forest, natural shrubs and thickets) through specific field sampling and laboratory tests, but it is still in the development stage (Manrique S, personal communication). In the same way, the environmental diversity and the complexity of the Lerma Valley system limit the extrapolation from punctual data to extensive generalizations.

The interpretation of the possible energy exploitation of the biomass resource is set forth in association with the diverse units of use and soil coverage. The base map of this variable was generated through the utilization of an unsupervised classification method by Menéndez et al. [22] and updated through visual interpretation of satellite images [21].

In order to correlate the available biomass energy resources with the use types and soil coverage, the last ones were grouped and reclassified in the following environmental units: urban areas, intensive agricultural and livestock production areas, natural forested areas, natural non-forested areas, bodies of water (dams), uncovered ground, thin vegetation, and water course.

A multicriteria evaluation of biomass availability was set up to identify the biomass resources with better perspectives for energy exploitation. This evaluation was specified through a qualitative–quantitative matrix which considered the following criteria: existence (volume or available area), degree of resource dispersion, accessibility, frequency, tendency, associated environmental impacts and use compatibility. They are defined in Table 1. The evaluation method used was a linear sum with weighing.

Finally, the biomass types identified as priority were compared at a general level through biomass quantitative indicators and energy estimations (through average values in those cases in which the necessary information is available).

In the case of the natural biomass, the possibility of its mapping is being analyzed through the digital processing of satellite images and the correlation of biomass values with vegetation indices, tasseled cap and/or analysis of the main components, but the reference values still have not been reached (Manrique S, personal communication).

2.4.2. Results

Fig. 4 show the available biomass types map, obtained from the use and soil coverage in Lerma Valley. From the multicriteria analysis of the different biomass types (4), the following kinds of energy availability came up: very high (importance value >500): agricultural waste (tobacco), urban solid waste (USW); high (450–500): sewage water; moderate to high (450–500): nature forested biomass; moderate (350–400): shrubs, brushes, pastures, cattle waste; low (300–350): sedimentation mud; and very low (<300): varied agricultural waste (vegetable and others).

As indicative values of this potential, some general parameters (questioned in the literature and in antecedents of the area) are specified for the different types of biomass identified as a priority. For the agricultural waste biomass (tobacco), whereas 20,000 ha/year cultivates in the Lerma Valley, a total volume of 2000 kg harvest/(ha year), waste index 0.5 kg/kg harvest and inferior calorific

Table 1
Criteria used for the evaluation of biomass availability in Lerma Valley.

Criteria	Weigh	Variable	Qualitative scale	Value
Existence	10	Available volume/surface of the associated coverage type	High	10
			Medium	7
			Low	2
Dispersion	9	Dispersion rank of the biomass resources	Concentrated	10
			Semi-dispersed	8
			Dispersed	2
Accessibility	9	Proximity to possible treatment centers. Distance–density. Communication nets	Accessible	10
			Moderately accessible	6
			Inaccessible	1
Temporality	8	Biomass production frequency	Continuous	10
			Periodic	8
			Irregular	1
Tendency	7	Probability of continuity of the resource generating source	Increasing	10
			Continuity in the long/medium term	9
			Unstable	4
Impact	7	Current environmental impact preventative measures	High	10
			Medium	6
			Low/indifferent	2
Use compatibility	6	Degree of competence with current uses—social acceptance	Compatible	10
			Moderately compatible	7
			Incompatible	2

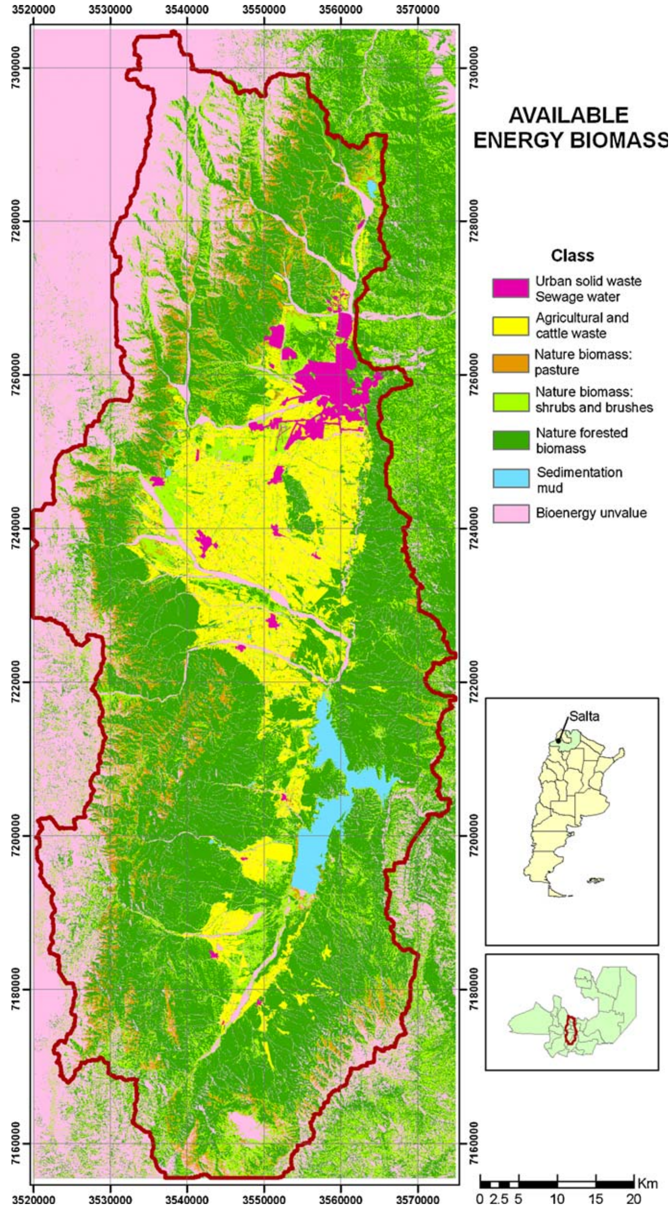

Fig. 4. Map of available energy biomass type.

power 3746.32 kCal/kg (Manrique S, personal communication), annual estimated useful energy is approximate to 156.6 MJ.[1]

In the case of USW, whereas an production of 450 t USW/day [39], efficiency index 0.68 MO/total USW and inferior calorific power 1000–2300 kCal/kg [35] (it depends on the USW composition, selection processes and treatment), average annual estimated useful energy is 2110.5 MJ.

2.4.3. Interpretation and discussion

Lerma Valley presents a high diversity of biomass resources with energy exploitation availability. The available volumes are variable depending on the considered biomass type. The most important limitations, associated with the energy availability, are related to the resource dispersion and its accessibility. Among the priority resources, the ones that stand out are: agricultural waste (tobacco), urban solid waste, and sewage water. The natural biomass potential is high for the wooded environmental units which present a large distribution in the work area.

This available biomass is susceptible to being exploited with an energetic purpose by industries, power stations (coal-fired or electric) and/or small family enterprises.

Technical aspects related to the real energy capacity of each type of biomass, together with economic, social and sustainability criteria must be evaluated in more detailed works in order to define energy exploitation viability on the basis of the identified biomass sources.

3. General conclusions

Lerma Valley presents a varied potential for energy exploitation of renewable resources in both the low area of the valley itself and in the mountainous areas. The estimated radiation values indicate a high potential for the whole area, proving a direct growth with the altitude. The wind power potential is moderate due to the valley narrowing and the roughness in hillsides with native forest, reaching representative values for exploitation only on the dividing line of the mountains. Regarding the hydraulic exploitation in microturbines, the western mountainous watersheds have the highest potential, associated with topographic characteristics of steep slopes and water flow resulting from orographic precipitation. The biomass potential, although qualitatively evaluated, indicates an important variability of the available resources, highlighting the possibility of exploiting agricultural waste biomass (tobacco) and urban biomass (urban solid waste and sewage water).

Regarding mapping methodologies, the utilization of GIS is a very powerful and significant tool for the definition and spatial evaluation of the renewable energy potential. The development of digital models allows obtaining spatial information for the totality of the studied territory covering basic information deficiencies which is generally scarce and dispersed. The models developed for each type of energy were adapted to the particular characteristics of each resource and energy source, promoting the software utilization and specific modules that could be extrapolated methodologically to other places and environmental conditions.

On the other hand, the evaluation of the energy potential constitutes a fundamental contribution to the definition of strategically planned energy policies. More detailed evaluations of economic, technical and social variables should be promoted in a parallel way, in order to develop integral and sustainable energy plans.

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